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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H04B

A2

(11) International Publication Number: **WO 99/49580**

(43) International Publication Date: 30 September 1999 (30.09.99)

(21) International Application Number: PCT/US99/06428

(22) International Filing Date: 24 March 1999 (24.03.99)

(30) Priority Data:
09/046,900 24 March 1998 (24.03.98) US

(71) Applicants: BANDWIDTH SOLUTIONS, INC. [US/US]; 2901 Hubbard, Ann Arbor, MI 48105 (US). THE REGENTS OF THE UNIVERSITY OF MICHIGAN [US/US]; Wolverine Tower, Room 2071, 3003 South State Street, Ann Arbor, MI 48109–1280 (US).

(72) Inventors: ISLAM, Mohammed, Nazrul; 2717 Holyoke Lane, Ann Arbor, MI 48103 (US). HARRIS, Hayden, Henry; 13875 Waters, Chelsea, MI 48118 (US).

(74) Agents: MORRIS, Francis, E. et al.; Pennie & Edmonds LLP, 1155 Avenue of the Americas, New York, NY 10036 (US).

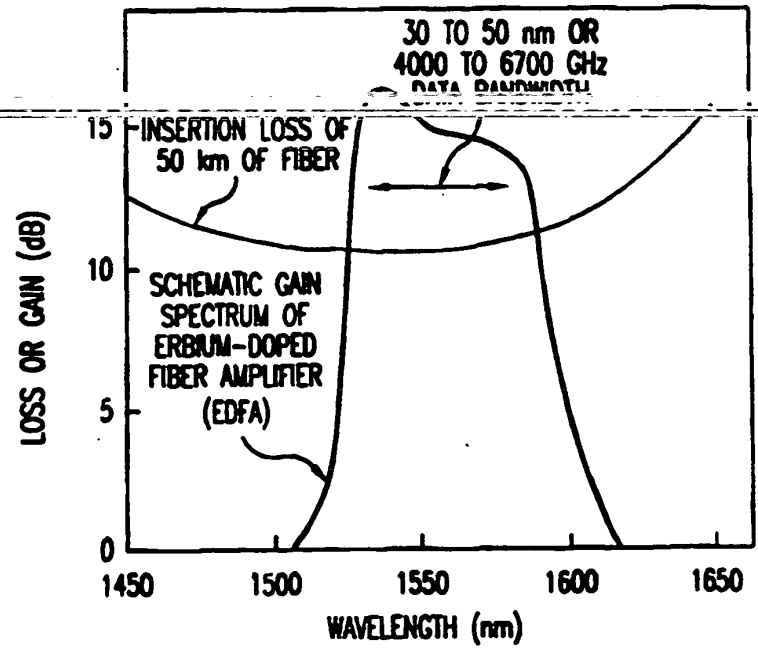
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: NONLINEAR FIBER AMPLIFIERS USED FOR A 1430–1530nm LOW-LOSS WINDOW IN OPTICAL FIBERS

(57) Abstract

An apparatus and method are described for exploiting almost the full almost 25THz of bandwidth available in the low-loss window 1620nm) using a parallel combination of optical amplifiers. The low-loss window at about 1530nm–1620nm can be amplified using erbium-doped fiber amplifiers (EDFAs). However, due to the inherent absorption of the erbium at shorter wavelengths, EDFAs cannot be used below about 1525nm without a significant degradation in performance. For the low-loss window at approximately 1430–1530nm, amplifiers based on nonlinear polarization in optical fibers can be used effectively. A broadband nonlinear polarization amplifier (NLPA) is disclosed which combines cascaded Raman amplification with parametric amplification or four-wave mixing. In particular, on of the intermediate cascade Raman order wavelengths λ_r sh uld lie in close proximity to the zero-dispersion wavelengths λ_0 of the amplifying fiber. For this intermediate Raman order, spectral broadening will occur due to phase-match with four-wave mixing (if $\lambda_r < \lambda_0$) or phase-matched parametric amplification (if $\lambda_r > \lambda_0$). In further cascaded Raman orders, the gain spectrum will continue t broaden due to the convolution of the gain spectrum with the spectrum from the previous Raman rder.



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NONLINEAR FIBER AMPLIFIERS USED FOR A 1430-1530nm LOW-LOSS WINDOW IN OPTICAL FIBERS

FIELD OF THE INVENTION

The present invention relates generally to optical amplifiers used in fiber-optics for telecommunications, cable television and other fiber-optics applications. More particularly, the invention relates to an optical fiber amplifier and method for producing an amplified broadband output from an optical signal having a wavelength in the range of 1430-1530nm.

BACKGROUND OF THE INVENTION

Because of the increase in data intensive applications, the demand for bandwidth in communications has been growing tremendously. In response, the installed capacity of telecommunication systems has been increasing by an order of magnitude every three to four years since the mid 1970s. Much of this capacity increase has been supplied by optical fibers that provide a four-order-of-magnitude bandwidth enhancement over twisted-pair copper wires.

To exploit the bandwidth of optical fibers, two key technologies have been developed and used in the telecommunication industry: optical amplifiers and

boost the signal strength and compensate for inherent fiber loss and other splitting and insertion losses. WDM enables different wavelengths of light to carry different signals parallel over the same optical fiber. Although WDM is critical in that it allows utilization of a major fraction of the fiber bandwidth, it would not be cost-effective without optical amplifiers. In particular, a broadband optical amplifier that permits simultaneous amplification of many WDM channels is a key enabler for utilizing the full fiber bandwidth.

Silica-based optical fiber has its lowest loss window around 1550nm with approximately 25THz of bandwidth

between 1430 and 1620nm. For example, Fig. 1 illustrates the loss profile of a 50km optical fiber. In this wavelength region, erbium-doped fiber amplifiers (EDFAs) are widely used. However, as indicated in Fig. 2, the absorption band of a EDFA nearly overlaps its the emission band. For wavelengths shorter than about 1525nm, erbium-atoms in typical glasses will absorb more than amplify. To broaden the gain spectra of EDFAs, various dopings have been added. For example, as shown in Fig. 3a, codoping of the silica core with aluminum or phosphorus broadens the emission spectrum considerably. Nevertheless, as depicted in Fig. 3b, the absorption peak for the various glasses is still around 1530nm.

Hence, broadening the bandwidth of EDFAs to accommodate a larger number of WDM channels has become a subject of intense research. As an example of the state-of-the-art, Y. Sun et al. demonstrated in Electronics Letters, Vol. 33, No. 23, pp. 1965-67 (1997), a two-band architecture for an ultra-wideband EDFA with a record optical bandwidth of 80nm. To obtain a low noise figure and high output power, the two bands share a common first gain section and have distinct second gain sections. The 80nm bandwidth comes from one amplifier (so-called conventional band or C-band) from 1525.6 to 1562.5nm and another amplifier (so-called long band or L-band) from 1569.4 to 1612.8nm. As another example, M. Yamada et al. reported in Electronics Letters, Vol. 33, No. 8, pp. 710-711 (1997), a 54nm gain bandwidth achieved with two EDFAs in a parallel configuration, i.e., one optimized for 1530-1560nm and the other optimized for 1576-1600nm. As yet another example, H. Masuda et al. reported in Electronics Letters, Vol. 33, No. 12, pp. 1070-72 (1997), a 52nm EDFA that used two-stage EDFAs with an intermediate equalizer.

These recent developments illustrate several points in the search for broader bandwidth amplifiers for the low-loss window in optical fibers. First, bandwidth in excess of 40-50nm require the use of parallel combination of amplifiers even with EDFAs. Second, the 80nm bandwidth achieved by Y.

Sun et al., may b very close to the theoretical maximum. The short wavelength side at about 1525nm is limited by the inherent absorption in erbium, and long wavelength side is limited by bend-induced losses in standard fibers at above 1620nm. Therefore, even with these recent advances, half of the bandwidth of the low-loss window, i.e., 1430-1530nm, remains without an optical amplifier.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an optical amplifier for a range of wavelengths between about 1430nm and 1530nm.

It is another object of the present invention to provide a broadband nonlinear polarization amplifier (NLPA) for generating a broadband output from an optical signal having a wavelength between about 1430nm and 1530nm.

It is yet another object of the present invention to provide a parallel optical amplification apparatus having a combination of the NLPA and EDFA for the almost full 25THz bandwidth between 1430nm and 1620nm in the low-loss window of optical fibers.

In accordance with the invention, a broadband NLPA is implemented by using a combination of cascaded Raman amplification and either parametric amplification (PA) or four-wave mixing (4WM) in optical fibers. To achieve the broad bandwidth, one intermediate order of the Raman cascade is arranged to be at a close proximity to the zero-dispersion wavelength of an amplifying fiber. This intermediate order phase matches PA (if its wavelength is greater than the zero-dispersion wavelength) or 4WM (if its wavelength is less than the zero-dispersion wavelength). PA/4WM generates sidebands and broaden the pump band. In subsequent Raman orders, the gain bandwidth is further broadened due to the convolution of the Raman gain band with the pump band. To produce an amplified broadband signal out of the NLPA of the invention, the optical signal to be amplified must have a wavelength greater than the zero-dispersion wavelength, which in turn

must be greater than the pumping wavelength from a pumping means of the NLPA.

In one embodiment, a broadband NLPA employs a 1240nm pump and an open-loop fiber with a zero-dispersion wavelength corresponding to one of the Raman orders (e.g., either 1310nm or 1390nm or dispersion-flattened in between). Another embodiment uses a Sagnac Raman cavity that is pumped at either 1117nm or 1240nm. Feedback by the Sagnac Raman cavity reduces the required pump power, and the broadband cavity design supports much of the generated bandwidth.

The present invention also relates to a parallel optical amplification apparatus having a combination of optical amplifiers. In one embodiment, the parallel optical amplification apparatus comprises two parallel stages of NLPAs with one NLPA optimized for 1430-1480nm and the other for 1480-1530nm. In another embodiment, the full 25THz of the low-loss window of approximately 1430nm to 1620nm in optical fibers is exploited by using a parallel combination of a NLPA of the invention and a EDFA.

NLPAs have the advantage that the gain band is set by the pumping wavelengths, and gain can be provided over virtually the entire transparency region in optical fibers (i.e., between 300nm and 2000nm). Moreover, because NLPAs utilize inherent properties of glass fibers, NLPAs can be used even in existing fibers by modifying the terminal ends. Hence, NLPAs are fully compatible with fiber-optic systems and can take advantage of the mature fiber-optic technologies.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects, features and elements of the present invention will be better understood from the following detailed description of preferred embodiments of the invention in which:

Fig. 1 depicts the loss profile of a 50km fiber and the gain band of a typical EDFA.

Fig. 2 depicts absorption and gain spectra of an EDFA.

Fig. 3a depicts emission spectra of four EDFAs with different core compositions.

Fig. 3b depicts absorption cross-section of erbium-doped glass of different compositions.

Fig. 4 depicts a measured Raman-gain spectrum for fused silica at a pump wavelength of 1000nm.

Fig. 5 plots power gain coefficient 2g versus phase vector mismatch Δk for parametric amplification.

Fig. 6 demonstrates basic concepts of the NLPA of the invention.

Fig. 7 illustrates the spectral broadening and gain expected from PA for a pump power of 1W and different separations between the pump and zero-dispersion wavelength.

Fig. 8 illustrates the spectral broadening and gain expected from PA for a pump and zero-dispersion wavelength separation of 1nm and for varying pump powers.

Fig. 9 is a schematic illustration of a first embodiment of an NLPA using an open-loop configuration.

Fig. 10 is a schematic illustration of a second embodiment of an NLPA using a Sagnac Raman cavity that is pumped at 1240nm.

Fig. 11 is a schematic illustration of a third embodiment of an NLPA using a Sagnac Raman cavity that is pumped at 1117nm.

Fig. 12 is a schematic illustration of a first embodiment of a parallel optical amplification apparatus having two stages of NLPAs.

Fig. 13 is a schematic illustration of a second embodiment of a parallel optical amplification apparatus that is a combination of an EDFA and an NLPA.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention provides a structure for exploiting almost the full 25THz of bandwidth available in the low-loss window of optical fibers from 1430nm to 1620nm.

The broadband NLPA amplifier of the invention combines Raman amplification with either PA or 4WM to achieve bandwidth performance improvements that neither technology by itself has heretofore been able to deliver.

More specifically, the broadband NLPA of the invention comprises an input port for inputting an optical signal having a wavelength λ, a distributed gain medium for receiving the optical signal and amplifying and spectrally broadening the same therein through nonlinear polarization, a pumping means operated at wavelength λ_p for generating a pumping light to pump the distributed gain medium, and an output port for outputting the amplified and spectrally broadened optical signal. The distributed gain medium has zero-dispersion at wavelength λ_0 such that $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light cascades through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

A first embodiment of the NLPA uses open-loop amplification with an optical fiber gain medium. A pump source operated at 1240nm is used. The pump may be retro-reflected to increase the conversion efficiency. A second embodiment of the NLPA uses a Sagnac Raman cavity that is pumped at 1240nm. Feedback in the Sagnac Raman cavity reduces the required pump power, and the broadband cavity design supports much of the generated bandwidth. A third embodiment of the NLPA uses a Sagnac Raman cavity pumped at 1117nm for a very broadband operation.

The present invention also relates to a parallel optical amplification apparatus having a combination of optical amplifiers. In one embodiment, the parallel optical amplification apparatus comprises two parallel stages of NLPAs with one NLPA optimized for 1430 to 1480nm and the other for 1480 to 1530nm. In another embodiment, the full 25THz of the low-loss window in optical fibers is exploited by using a parallel combination of a Raman amplifier and a

rare earth doped amplifier. Preferably, an NLPA of the invention is used cover the low-loss window of approximately 1430nm to 1530nm, and an EDFA is used to cover the low-loss window of approximately 1530nm to 1620nm.

To provide a better understanding of the amplification mechanisms at work in the present invention, we first describe stimulated Raman scattering, Raman cascading, PA and 4WM. Stimulated Raman scattering effect, PA and 4WM are the result of third-order nonlinearities that occur when a dielectric material such as an optical fiber is exposed to intense light. The third-order nonlinear effect is proportional to the instantaneous light intensity.

1. Stimulated Raman Scattering

Stimulated Raman scattering is an important nonlinear process that turns optical fibers into amplifiers and tunable lasers. Raman gain results from the interaction of intense light with optical phonons in silica fibers, and Raman effect leads to a transfer of energy from one optical beam (the pump) to another optical beam (the signal). The signal is downshifted in frequency (or upshifted in wavelength) by an amount determined by vibrational modes of silica fibers. The Raman gain coefficient g_r for the silica fibers is shown in Fig. 4. Notably, the Raman gain g_r extends over a large frequency range (up to 40THz) with a broad peak centered at 13.2THz (corresponding to a wavelength of 440 cm^{-1}). This behavior over the large frequency range is due to the amorphous nature of the silica glass and enables the Raman effect to be used in broadband amplifiers. The Raman gain also depends on the composition of the fiber core and can vary with different dopant concentrations.

Raman amplification has some attractive features. First, Raman gain is a good candidate for upgrading existing fiber optic links because it is based on the interaction of pump light with optical phonons in the existing fibers. Second, there is no excessive loss in the absence of pump power - an important consideration for system reliability.

2. Raman Cascading

Cascading is the mechanism by which optical energy at the pump wavelength is transferred, through a series of nonlinear polarizations, to an optical signal at a longer wavelength. Each nonlinear polarization of the dielectric produces a molecular vibrational state corresponding to a wavelength that is offset from the wavelength of the light that produced the stimulation. The nonlinear polarization effect is distributed throughout the dielectric, resulting in a cascading series of wavelength shifts as energy at one wavelength excites a vibrational mode that produces light at a longer wavelength. This process can cascade through numerous orders. Because the Raman gain profile has a peak centered at 13.2THz in silica fibers, one Raman order can be arranged to be separated from the previous order by 13.2THz.

Cascading makes stimulated Raman scattering amplifiers very desirable. Raman amplification itself can be used to amplify multiple wavelengths (as in wavelength division multiplexing) or short optical pulses because the gain spectrum is very broad (a bandwidth of greater than 5THz around the peak at 13.2THz). Moreover, cascading enables Raman amplification over a wide range of different wavelengths. By varying the pump wavelength or by using cascaded orders of Raman gain, the gain can be provided over the entire telecommunications window between 1300nm and 1600nm.

3. Parametric Amplification and Four-Wave Mixing

PA/4WM involve two pump (P) photons that create Stokes (S) and anti-Stokes (A) photons. Both PA/4WM and Raman amplification arise from the third order susceptibility $\chi^{(3)}$ in optical fibers. More specifically, the real part of $\chi^{(3)}$, the so-called nonlinear index of refraction n_2, is responsible for PA/4WM, while the imaginary part of $\chi^{(3)}$ associated with molecular vibrations corresponds to the Raman gain effect. In silica fibers, about 4/5ths of the n_2 is an

electronic, instantaneous nonlinearity caused by ultraviolet resonances, while about 1/5th of n_2 arises from Raman-active vibrations, e.g., optical phonons (see further description in M.N. Islam, Ultrafast Fiber Switching Devices and Systems, Cambridge University Press, 1992). The imaginary part of this latter contribution corresponds to the Raman gain spectrum of Fig. 4.

Whereas Raman amplification is attractive for providing optical gain, PA/4WM offers an efficient method to broaden the bandwidth of the optical gain. PA/4WM has a much smaller frequency separation between pump and signal than Raman amplification, and the frequency difference may depend on the pump intensity. Just as in Raman amplification, the main advantage of PA/4WM gain is that it is present in every fiber. However, unlike the Raman effect, both PA and 4WM require phase-matching. 4WM is usually inefficient in long fibers due to the requirement for phase-matching. However, PA can act as self-phase-matched because the nonlinear index of refraction is used to phase match the pump and sidebands. This is particularly true when operating near the zero-dispersion wavelength in fibers. When 4WM and PA occur near the zero-dispersion wavelength of a single-mode fiber, phase-matching becomes automatic in the fiber. In 4WM, sidebands are generated without gain when the pump wavelength falls in the normal dispersion regime (where the pumping wavelength is shorter than the zero-dispersion wavelength). PA is 4-photon amplification in which the nonlinear index of refraction is used to phase match the pump and sidebands. For PA the pump wavelength must lie in the anomalous group velocity regime (i.e., where the pumping wavelength is longer than the zero-dispersion wavelength) and proper phase matching requires that pump and signal be co-propagating.

To illustrate the PA/4WM gain, consider the gain coefficient as derived in R.H. Stolen and J.E. Bjorkholm, IEEE J. Quantum Elect., QE-18, 1062 (1982):

$$g = \sqrt{(\gamma P)^2 - \left[\left(\frac{\Delta\kappa}{2}\right) + \gamma P\right]^2} \qquad (1)$$

The first term under the square root sign corresponds to the third order nonlinearity that couples the pump photons to the sidebands. The second term corresponds to the phase mismatch between the waves and it consists of two parts: one due to the wave-vector mismatch at the different wavelengths and the other due to the increase in nonlinear index induced by the pump. The nonlinearity parameter is defined as

$$\gamma = \frac{\omega}{c}\frac{n_2}{A_{eff}} = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \qquad (2)$$

Also, assuming that we are operating near the zero-dispersion wavelength λ_0, the propagation constant can be expanded as

$$\Delta\kappa = -\frac{\lambda^2}{2\pi c}\left[\frac{dD}{d\lambda}\bigg|_{\lambda_o}\left(\lambda_p - \lambda_o\right)\right]\Omega^2 \qquad (3)$$

where

$$\Omega = \omega_p - \omega_s = \omega_a - \omega_p. \qquad (4)$$

When the pump wavelength falls in the normal dispersion regime, then $D < 0$, $\partial D/\partial\lambda > 0$, $(\lambda_p - \lambda_0) < 0$, so that $\Delta k > 0$. In this case, g is always imaginary, and there is no gain during the sideband generation process. This corresponds to the case of 4WM. If operation is in the anomalous group velocity dispersion regime, then $D > 0$, $\partial D/\partial\lambda > 0$, $(\lambda_p - \lambda_o) > 0$, so that $\Delta k < 0$. This is the regime of PA, and the nonlinearity helps to reduce the phase mismatch (i.e., the two parts in the second term in Equation (1) are of opposite sign). There is gain for PA, and the gain is tunable with the pump power. As an example, the power gain coefficient 2g

is plotted schematically in Fig. 5 for operation in the anomalous group velocity regime. The peak gain ($g_{peak}=\gamma P$) occurs at $\Delta k_{peak}=-2\gamma P$. The range over which the gain exists is given by $0 > \Delta k > -4\gamma P$. Thus, the peak gain is proportional to the pump power, and the Δk range is determined by the pump power. Consequently, from Equation (2) we see that the bandwidth can be increased by increasing the pump power, increasing the nonlinear coefficient n_2 or decreasing the effective area A_{eff}. Alternately, for a given required frequency range over which gain is required, the pump requirements can be reduced by increasing the effective nonlinearity (n_2/A_{eff}).

4. Broadband NLPA by Combining Raman and Either PA or 4WM

This invention leads to broadband gain for cascaded Raman amplification by arranging at least one intermediate Raman cascade order at a close proximity to the zero-dispersion wavelength λ_0 (e.g., within ±5nm of λ_0, optimally within ±2nm). Either 4WM (if $\lambda_r < \lambda_0$) or PA (if $\lambda_r > \lambda_0$) will lead to spectral broadening of that particular Raman order. Then, in subsequent Raman orders the bandwidth will grow even further. It is further advantageous if the cascade Raman wavelength λ_r lies to the long wavelength side of λ_0 (i.e., in the anomalous dispersion regime), so that parametric amplification can occur.

The basic concept of the broadband NLPA is illustrated in Fig. 6. Starting from the pump wavelength λ_p, cascaded Raman amplification can be used in the first few stages. This is only if the pump is more than one Raman shift or 13.2THz away from the zero-dispersion wavelength. (If it is desired to keep higher efficiency in these initial steps, a narrow band cavity design can be used, such as designs based on gratings or wavelength selective couplers.)

The key to the invention of broadening the gain bandwidth is that one of the intermediate Raman cascade orders lies at a close proximity to the zero-dispersion wavelength λ_0. By operating close to λ_0, it almost

automatically phase-matches either 4WM or PA. In the subsequent cascaded Raman orders, the gain bandwidth may continue to broaden. This occurs because the effective gain bandwidth of Raman is the convolution of the bandwidth of the pump (in this case, the previous Raman cascade order) with the Raman gain curve. In this regard, see discussion in R.H. Stolen, et al., "Development of the stimulated Raman spectrum in single-mode silica fibers," Journal of the Optical Society of America B, Vol. 1 (1984), pp. 652-57. Thus, the basic idea is to take advantage of the property of Raman amplification that the gain spectrum follows the pump spectrum. As the pump wavelength changes, the Raman gain changes as well, separated by the distance of optical phonon energy which in silica fibers is an approximately 13.2THz down-shift in frequency.

If the fiber is conventional so-called standard fiber, then zero-dispersion wavelength λ_0 is about 1310nm. On the other hand, for dispersion-shifted fiber the zero-dispersion wavelength λ_0 can shift to longer wavelengths by adding waveguide dispersion. Alternately, a dispersion-flattened fiber could be used for low dispersion values over one or more of the Raman cascade orders. The additional advantage of using dispersion-flattened fiber is that the dispersion slope is small, so the gain bandwidth will be even larger (c.f. Equations (1) and (3)).

The Raman gain spectrum can follow the pump spectrum only so long as there is nothing in the Raman cavity to restrict the bandwidth of the subsequent orders. Therefore, for these higher cascade orders Raman laser schemes, it is not desirable to use either gratings or wavelength selective couplers. On the other hand, the broadband cavity design of the Sagnac Raman amplifier and laser lends itself naturally to increased bandwidth by tailoring the pump spectrum. A single-pass fiber design constitutes the broadest bandwidth design. However, a broadband cavity such as the Sagnac Raman cavity is advantageous because the feedback is used to lower the

threshold and the required pump power. Also, it should be noted that broadening the bandwidth leads to a drop in efficiency, so the pump powers are already higher for the broadband cavity designs.

5. Example of NLPA Gain Broadening from PA and Cascaded Raman

To illustrate the cascaded Raman amplification to reach the 1430-1530nm range of the low-loss window, consider pumping with a commercially available cladding-pumped fiber laser, which operates around 1060 to 1140nm. The various Raman orders, each separated by 13.2Thz from the previous order, are set forth in Table 1.

Table 1. Various Raman orders when pumping between 1060 and 1140nm (separation of 13.2THz between orders)

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1060.00	51.86	1110.00	57.00
1111.86	57.19	1167.00	63.17
1169.05	63.39	1230.16	70.40
1232.44	70.66	1300.56	78.94
1303.11	79.26	1379.50	89.14
1382.37	89.53	1468.64	101.46
1471.90	101.93	1570.10	116.52
1573.82	117.09	1686.62	135.20

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1070.00	52.86	1117.00	57.74
1122.86	58.36	1174.74	64.03
1181.22	64.76	1238.77	71.41
1245.98	72.27	1310.18	80.15
1318.25	81.17	1390.33	90.59
1399.42	91.82	1480.92	103.22
1595.97	120.54	1702.84	137.92

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1080.00	53.88	1120.00	58.05
1133.88	59.54	1178.05	64.40
1193.42	66.14	1242.46	71.85
1259.56	73.90	1314.31	80.67
1333.47	83.11	1394.98	91.22
1416.58	94.16	1486.20	103.99
1510.74	107.57	1590.19	119.63
1618.32	124.07	1709.82	139.10

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1090.00	54.91	1130.00	59.12
1144.91	60.74	1189.12	65.65
1205.65	67.54	1254.77	73.32
1273.19	75.56	1328.10	82.43
1348.74	85.09	1410.53	93.33
1433.83	96.55	1503.86	106.56
1530.38	110.49	1610.42	122.81
1640.87	127.69	1733.24	143.09

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1100.00	55.95	1140.00	60.20
1155.95	61.94	1200.20	66.92
1217.89	68.96	1267.12	74.82
1286.85	77.24	1341.93	84.21
1364.09	87.10	1426.14	95.48
1451.19	98.98	1521.62	109.18
1550.17	113.47	1630.81	126.07
1663.64	131.40	1756.87	147.19

To obtain gain between 1430nm and 1520nm, the pump is operated between 1090nm and 1140nm, and five cascaded Raman orders are used to reach the desired wavelength. To make use of the broadening from PA or 4WM, a pumping scheme is selected in the middle of this range, i.e., starting with a pump wavelength of 1117nm. Then, the various Raman orders land at approximately 1175nm, 1240nm, 1310nm, 1390nm and finally 1480nm. In particular, the third Raman frequency (1310nm) passes through the zero-dispersion point of a standard fiber, and the next order (1390nm) could be close if the fiber is dispersion shifted. Therefore, a broadband gain is expected for wavelengths in the 1430-1530nm range centered around 1480nm by using a fiber with a standard dispersion and a pump wavelength of 1117nm, 1175nm or 1240nm.

Next, consider the broadening expected from PA. Assume that a standard fiber is used and the pump wavelength starts at 1117nm. The calculations use Equations (1-4) with the following typical parameters for high-Raman cross-section fiber: λ_0 = 1310nm, γ = 9.9$W^{-1}km^{-1}$, and a dispersion slope of 0.05ps/nm-km. In Fig. 7, the gain coefficient for PA is plotted versus wavelength at a pump power of 1W and wavelength separations ($\lambda_r-\lambda_0$) of 0.5, 1, 2 and 5nm. For a wavelength separation of 2nm, the PA peak gain occurs at ±10nm, so the spectral broadening is over 20nm. The closer the pump wavelength approaches the zero-dispersion wavelength, the wider the gain bandwidth. In addition, Fig. 8 plots the gain versus wavelength for a separation of ($\lambda_r-\lambda_0$)=1nm and pump powers of 0.7, 1, 2, and 3W. The peak gain increases directly proportional to the pump power, while the bandwidth increases as the square root of pump power.

6. Preferred Embodiments of NLPA Amplifiers

Fig. 9 shows a first embodiment of the invention which uses an open-loop design to produce an amplified broadband signal for a range of wavelengths between 1430nm and 1530nm. The open-loop design is the simplest nonlinear polarization amplifier although it may have a high pump power requirement. In the NLPA amplifier 20 as illustrated in Fig. 9, an optical signal having a wavelength between 1430nm and 1530nm is input from an input port 25 to an optical fiber 30. The optical fiber 30 is pumped by a pumping light generated by a pumping laser 35 operated at a wavelength of about 1240nm. The optical signal is amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 40. The configuration is so arranged that the optical signal has a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn is greater than the pumping wavelength of 1240nm.

In this open-loop configuration, the fiber must have a cut-off wavelength below 1240nm to be single-mode (spatial) over all wavelengths of the Raman cascade. Three choices of the fiber are preferred in this configuration. First, a standard dispersion fiber with a zero-dispersion wavelength at about 1310nm. Second, two fibers spliced together with one fiber having a zero-dispersion wavelength at about 1310nm (first cascade) and the other at 1390nm (second cascade). Third, a dispersion-flattened fiber with low-dispersion at least between 1310nm and 1390nm. The reduced dispersion slope of such a dispersion-flattened fiber increases significantly the bandwidth for PA or 4WM.

Exemplary 1240nm pump lasers include: (a) an 1117nm cladding-pumped fiber laser followed by a coupler-based or grating-based Raman oscillator cavity (with gratings for 1117nm, 1175nm and 1240nm); (b) an optically-pumped semiconductor laser; or (c) a chromium-doped forsterite laser. At one end of the fiber, a 1240nm retro-reflector 45 is preferably placed to increase pumping conversion efficiency. The retro-reflector is preferably a dichroic

mirror or a 1240nm grating. The input and output ports are preferably WDM couplers, and isolators should be used at the input and output ports to prevent from lasing due to spurious feedback. It is desirous to use a counter-propagating geometry to average out noise fluctuations in this open-loop configuration. It is also possible to use a co-propagating geometry.

To reduce the pump power requirements, a broadband cavity such as the Sagnac Raman cavity is used. Fig. 10 illustrates an embodiment of the NLPA that uses a Sagnac Raman cavity design with a 1240nm pump. Referring to Fig. 10, the Sagnac Raman cavity of the NLPA 60 is formed by a broadband mirror 70 and a loop mirror comprising a Raman gain fiber 65 and an optical coupler 90 connected thereto. The Sagnac Raman cavity design is described in a U.S. patent application serial no. 08/773,482, and this patent application is incorporated herein by reference. An optical signal having a wavelength between 1430nm to 1530nm is input through an input port 75 to the Raman gain fiber 65. A pumping laser 80 operated at a wavelength 1240nm generates a pumping light that pumps the fiber 65 through a coupling means 85. The optical signal is amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 95. The configuration is so arranged that the optical signal has a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn is greater than the pumping wavelength of 1240nm.

The Raman gain fiber has the same characteristics as described above for the open-loop design. Similarly, the pumping lasers used in the first embodiment are used in this second embodiment. The broadband NLPA may further include a polarization controller 100 in the Sagnac Raman cavity for controlling polarization state. However, if the fiber is polarization maintained, the polarization controller is not necessary. The optical coupler 90 is nominally 50:50 at least for the optical signal having a wavelength between about 1240nm and 1430nm. The coupling means 85 is a WDM

coupler which transmits at least at a wavelength between about 1300nm and 1430nm. Moreover, the input port and output port each comprises a WDM coupler which transmits at least at a wavelength between about 1240nm and 1425nm. A key advantage of the Sagnac Raman cavity is that it has a passive noise dampening property that leads to quieter cascading of various Raman orders.

As an alternative, the same kind of Sagnac Raman cavity can be used for all five Raman cascade orders between 1117nm and the low-loss window. Fig. 11 illustrates a third embodiment of a five-order Sagnac Raman amplifier for NLPA operation. A cladding-pumped fiber laser operating around 1117nm is used as a pumping laser 120. Different fiber combinations described in the first embodiment can be used except that the fibers must have a cut-off wavelength below 1117nm to accommodate single-mode operation for the pump. An optical coupler 130 is nominally 50:50 at least for the optical signal having the wavelength between about 1117nm and 1430nm. A coupling means 125 is a WDM coupler which transmits at least at wavelengths between about 1165nm and 1430nm. Moreover, the input and output ports each comprises a WDM coupler which transmits at least at wavelengths between about 1117nm and 1425nm. Although the wavelength range of the various components increases, this configuration leads to to increase even during the first two cascades between 1117nm and 1240nm. Also, the noise dampening property of the Sagnac cavity can be used advantageously over all five Raman orders.

In general, the NLPA is operated as follows. An optical signal having a wavelength λ is input through an input port into a distributed gain medium having zero-dispersion at a wavelength λ_0, such as an optical fiber, which is pumped by a pumping light from a pumping means operated at a wavelength λ_p, wherein $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light cascades through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion

wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$). The amplified and spectrally broadened optical signal is output through an output port.

7. Broadband Parallel Optical Amplification Apparatus

The above embodiments demonstrate that a single NLPA can accommodate the full bandwidth of the low-loss window. Moreover, the full bandwidth of the low-loss window may be reached by using a parallel optical amplification apparatus having a combination of two or more Raman amplifiers and rare earth doped amplifiers. Preferably, the NLPAs and EDFAs are used.

Fig. 12 shows a first embodiment of the parallel optical amplification apparatus using a combination of two NLPAs for a range of wavelengths between 1430nm and 1530nm. Referring to Fig. 12, a dividing means 170 divides an optical signal having a wavelength between 1430nm to 1530nm at a predetermined wavelength, preferably at 1480nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength. The first beam is input into a first NLPA 180 for amplification and spectral broadening therein. The second beam is input into a second NLPA 190 for amplification and spectral broadening therein. Outputs from the first and second NLPAs are combined by a combining means 200 to produce an amplified and spectrally broadened optical signal. The input port 170 and output port 200 are preferably WDM couplers.

It is preferred that the first NLPA 180 is optimized for 1430-1480nm and centered at 1455nm, while the second NLPA is optimized for 1480-1530nm and centered at 1505nm. From Table 1, these two windows can be achieved in a five-order cascade by starting with a pump wavelength of about 1100nm for the short-wavelength side and a pump wavelength of about 1130nm for the long-wavelength side. For the short-wavelength side, the fiber should have a zero-

dispersion around 1365nm, while for the long-wavelength side, the fiber zero-dispersion should be around 1328nm or 1410nm.

The narrower-bandwidth for each NLPA will also lead to an increased efficiency for each amplifier. Furthermore, the components may be more easily manufactured, since the wavelength window is not as large. Finally, the multiple amplifiers may allow for gradual upgrades of systems, adding bandwidth to the EDFA window as needed.

A spectrum of 1430-1620nm in the low-loss window is amplified and spectrally broadened by using a parallel optical amplification apparatus comprising Raman amplifiers and rare earth doped amplifiers. Fig. 13 describes a second embodiment of the parallel optical amplification apparatus. The amplification apparatus comprises a broadband NLPA 240 as disclosed in this invention and a EDFA 250. A dividing means 230 of the apparatus divides an optical signal having a wavelength between 1430nm and 1620nm at a predetermined wavelength, preferably at 1525nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength. The broadband NLPA 240 receives the first beam and produces an amplified broadband first beam. The EDFA 250 receives the second beam and produces an amplified broadband second beam. A combining means 260 second beams to produce an amplified broadband optical signal. It is preferred that both the dividing means 230 and the combining means 260 are WDM couplers.

To use any of these embodiments with multi-wavelength WDM channels, it will most likely be necessary to include at the output of the amplifier some means for equalizing the gain. This wavelength dependency or nonuniformity of the gain band has little impact on single-channel transmission. However, it renders the amplifier unsuitable for multichannel operation through a cascade of amplifiers. As channels at different wavelengths propagate through a chain of amplifiers, they accumulate increasing

discrepancies between them in terms of gain and signal-to-noise ratio. Using gain-flattening elements can significantly increase the usable bandwidth of a long chain of amplifiers. For example, the NLPA can be followed by a gain flattening element to provide gain equalization for different channels. Alternately, the gain flattening element could be introduced directly into the Sagnac interferometer loop of Figs. 10 or 11.

It is understood that various other modifications will be readily apparent to those skilled in the art without departing from the scope and spirit of the invention. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the description set forth herein, but rather that the claims be construed as encompassing all the features of the patentable novelty that reside in the present invention, including all features that would be treated as equivalents thereof by those skilled in the art to which this invention pertains.

WHAT IS CLAIMED IS:

1. A broadband nonlinear polarization amplifier comprising:

an input port for inputting an optical signal having a wavelength λ;

a distributed gain medium for receiving said optical signal and amplifying and spectrally broadening said optical signal therein through nonlinear polarization, said distributed gain medium having zero-dispersion at wavelength λ_0;

a pumping means operated at wavelength λ_p for generating a pumping light to pump said distributed gain medium; and

an output port for outputting said amplified and spectrally broadened optical signal,

wherein $\lambda \geq \lambda_0 \geq \lambda_p$, and

said pumping light cascades through said distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

2. The broadband nonlinear polarization amplifier according to claim 1, wherein said wavelengths λ_r and λ_0 satisfy the following relationship:

$$|\lambda_r - \lambda_0| \leq 5\text{nm}.$$

3. The broadband nonlinear polarization amplifier according to claim 1, wherein said distributed gain medium is an optical fiber.

4. The broadband nonlinear polarization amplifier according to claim 1, wherein said distributed gain medium is a standard dispersion fiber having a zero-dispersion wavelength λ_0 of about 1310nm.

5. The broadband nonlinear polarization amplifier according to claim 1, wherein said distributed gain medium comprises first and second optical fibers spliced together, and said optical fibers are used for two different cascaded Raman orders and have a zero-dispersion wavelength λ_0 at about 1310nm and 1390nm respectively.

6. The broadband nonlinear polarization amplifier according to claim 1, wherein said distributed gain medium is a dispersion-flattened fiber with low dispersion at least between about 1310nm and 1390nm.

7. The broadband nonlinear polarization amplifier according to claim 1, wherein said pumping wavelength λ_p is at about 1117nm.

8. The broadband nonlinear polarization amplifier according to claim 1, wherein said pumping wavelength λ_p is at about 1240nm.

9. The broadband nonlinear polarization amplifier according to claim 1, wherein said optical signal has a wavelength λ at least between about 1430nm and 1530nm.

10. The broadband nonlinear polarization amplifier according to claim 1, wherein said pumping means is an optically-pumped semiconductor laser.

11. The broadband nonlinear polarization amplifier according to claim 1, wherein said pumping means is a chromium-doped forsterite laser.

12. The broadband nonlinear polarization amplifier according to claim 1, wherein said pumping means is a cladding-pumped fiber laser followed by a grating-based Raman oscillator.

13. The broadband nonlinear polarization amplifier according to claim 1, wherein said input port comprises a WDM coupler.

14. The broadband nonlinear polarization amplifier according to claim 1, wherein said output port comprises a WDM coupler.

15. A broadband nonlinear polarization amplifier comprising:

an input port for inputting an optical signal having a wavelength λ;

an optical fiber for receiving said optical signal and amplifying and spectrally broadening said optical signal therein through nonlinear polarization, said optical fiber having zero-dispersion at wavelength λ_0 and a cut-off wavelength less than 1240nm;

a pumping means operated at wavelength 1240nm for generating a pumping light to pump said optical fiber; and

an output port for outputting said amplified and spectrally broadened optical signal,

wherein $\lambda \geq \lambda_0 \geq 1240nm$, and

said pumping light cascades through said optical fiber a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

16. The broadband nonlinear polarization amplifier according to claim 15, further comprising a retroreflector operated at 1240nm and connected to said optical fiber for increasing pumping conversion efficiency.

17. The broadband nonlinear polarization amplifier according to claim 16, wherein said retroreflector is a dichroic mirror.

18. The broadband nonlinear polarization amplifier according to claim 16, wherein said retroreflector is a 1240nm grating.

19. The broadband nonlinear polarization amplifier according to claim 15, wherein said optical fiber is a standard dispersion fiber having a zero-dispersion wavelength λ_0 of about 1310nm.

20. The broadband nonlinear polarization amplifier according to claim 15, wherein said optical fiber comprises first and second optical fibers spliced together, said first optical fiber has a zero-dispersion wavelength at about 1310nm used for one cascaded Raman order, and said second optical fiber has a zero-dispersion wavelength at about 1390nm used for another cascaded Raman order.

21. The broadband nonlinear polarization amplifier according to claim 15, wherein said optical fiber is a dispersion-flattened fiber with low dispersion at least between about 1310nm and 1390nm.

22. The broadband nonlinear polarization amplifier according to claim 15, wherein said optical signal has a wavelength between about 1430nm and 1530nm.

23. The broadband nonlinear polarization amplifier according to claim 15, wherein said pumping means is a 1117nm cladding-pumped fiber laser followed by a coupler-based or grating-based Raman oscillator cavity.

24. The broadband nonlinear polarization amplifier according to claim 15, wherein said pumping means is an optically-pumped semiconductor laser.

25. The broadband nonlinear polarization amplifier according to claim 15, wherein said pumping means is a chromium-doped forsterite laser.

26. The broadband nonlinear polarization amplifier according to claim 15, wherein said input port comprises a WDM coupler.

27. The broadband nonlinear polarization amplifier according to claim 26, wherein said input port further comprises an isolator for preventing said amplifier from lasing due to spurious feedback.

28. The broadband nonlinear polarization amplifier according to claim 15, wherein said output port comprises a WDM coupler.

29. The broadband nonlinear polarization amplifier according to claim 28, wherein said output port further comprises an isolator for preventing said amplifier from lasing due to spurious feedback.

30. A broadband nonlinear polarization amplifier comprising:

an input port for inputting an optical signal having a wavelength between about 1430nm and 1530nm;

a Sagnac Raman cavity comprising

a broadband mirror, and

a loop mirror comprising a Raman gain fiber and an optical coupler connected thereto, said fiber receiving said optical signal and amplifying and spectrally broadening said optical signal therein through nonlinear polarization, said fiber having zero-dispersion at wavelength λ_0 and a cut-off wavelength λ_{co};

a pumping means operated at a wavelength λ_p for generating a pumping light to pump said fiber through a coupling means; and

an output port for outputting said amplified and spectrally broadened optical signal,

wherein 1430nm $\geq \lambda_0 \geq \lambda_p$, and

said pumping light cascades through said distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

31. The broadband nonlinear polarization amplifier according to claim 30, further comprising a polarization controller in said Sagnac Raman cavity for controlling polarization state.

32. The broadband nonlinear polarization amplifier according to claim 30, wherein said fiber is a standard dispersion fiber having a zero-dispersion wavelength λ_0 of about 1310nm.

33. The broadband nonlinear polarization amplifier according to claim 30 wherein said fiber comprises first and second optical fibers spliced together, and said optical fibers are used for two different cascaded Raman orders and have a zero-dispersion wavelength λ_0 at about 1310nm and 1390nm respectively.

34. The broadband nonlinear polarization amplifier according to claim 15, wherein said fiber is a dispersion-flattened fiber with low dispersion at least between about 1310nm and 1390nm.

35. The broadband nonlinear polarization amplifier according to claim 30, wherein said pumping means is an optically-pumped semiconductor laser.

36. The broadband nonlinear polarization amplifier according to claim 30, wherein said pumping means is a chromium-doped forsterite laser.

37. The broadband nonlinear polarization amplifier according to claim 30, wherein said cut-off wavelength λ_{co} and said pumping wavelength are both about 1240nm.

38. The broadband nonlinear polarization amplifier according to claim 37, wherein said optical coupler is nominally 50:50 at least for said optical signal having the wavelength between about 1240nm and 1430nm.

39. The broadband nonlinear polarization amplifier according to claim 37, wherein said coupling means comprises a WDM coupler which transmits at least at a wavelength between about 1300nm and 1430nm.

40. The broadband nonlinear polarization amplifier according to claim 37, wherein said input port and output port each comprises a WDM coupler which transmits at least at a wavelength between about 1240nm and 1425nm.

41. The broadband nonlinear polarization amplifier according to claim 30, wherein said pumping means is a 1117nm cladding-pumped fiber laser followed by a coupler-based or grating-based Raman oscillator cavity.

42. The broadband nonlinear polarization amplifier according to claim 30, wherein said cut-off wavelength λ_{co} and said pumping wavelength each is about 1117nm.

43. The broadband nonlinear polarization amplifier according to claim 42, wherein said optical coupler is nominally 50:50 at least for said optical signal having the wavelength between about 1117nm and 1430nm.

44. The broadband nonlinear polarization amplifier according to claim 42, wherein said coupling means comprises a WDM coupler which transmits at least at a wavelength between about 1165nm and 1430nm.

45. The broadband nonlinear polarization amplifier according to claim 43, wherein said input port and output port each comprises a WDM coupler which transmits at least at a wavelength between about 1117nm and 1425nm.

46. A broadband parallel optical amplification apparatus, said apparatus comprising:

a dividing means for dividing an optical signal having a wavelength between 1430nm to 1530nm at a predetermined wavelength λ_d into a first beam having a wavelength λ_1 less than λ_d and a second beam having a wavelength λ_2 greater than λ_d;

a first broadband nonlinear polarization amplifier comprising

a first input port for inputting said first beam;

a first distributed gain medium for receiving said first beam and amplifying and spectrally broadening said first beam therein through nonlinear polarization, said first distributed gain medium having zero-dispersion at wavelength λ_{01};

a first pumping means operated at wavelength λ_{p1} for generating a first pumping light to pump said first distributed gain medium; and

a first output port for outputting said amplified and spectrally broadened first beam,

wherein $\lambda_1 \geq \lambda_{01} \geq \lambda_{p1}$, and

said first pumping light cascades through said first distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_{r1} at a close proximity to said zero-dispersion wavelength λ_{01} to

phase match four-wave mixing (if $\lambda_{r1} < \lambda_{01}$) or parametric amplification (if $\lambda_{r1} > \lambda_{01}$);

a second broadband nonlinear polarization amplifier comprising

a second input port for inputting said second beam;

a second distributed gain medium for receiving said second beam and amplifying and spectrally broadening said second beam therein through nonlinear polarization, said second distributed gain medium having zero-dispersion at wavelength λ_{02};

a second pumping means operated at wavelength λ_{p2} for generating a second pumping light to pump said second distributed gain medium; and

a second output port for outputting said amplified and spectrally broadened second beam,

wherein $\lambda_2 \geq \lambda_{02} \geq \lambda_{p2}$, and

said second pumping light cascades through said second distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_{r2} at a close proximity to said zero-dispersion wavelength λ_{02} to phase match four-wave mixing (if $\lambda_{r2} < \lambda_{02}$) or parametric amplification (if $\lambda_{r2} > \lambda_{02}$); and

means for combining said amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal.

47. The optical signal amplification apparatus according to claim 46, wherein said predetermined wavelength λ_d is about 1480nm.

48. The optical signal amplification apparatus according to claim 46, wherein said first gain medium has said zero-dispersion wavelength λ_{01} of about 1365nm.

49. The optical signal amplification apparatus according to claim 46, wherein said second gain medium has said zero-dispersion wavelength λ_{02} of about 1328nm.

50. The optical signal amplification apparatus according to claim 46, wherein said pumping wavelength λ_{p1} is about 1100nm.

51. The optical signal amplification apparatus according to claim 46, wherein said pumping wavelength λ_{p2} is about 1130nm.

52. The optical signal amplification apparatus according to claim 46, wherein said dividing means comprises a WDM coupler.

53. The optical signal amplification apparatus according to claim 46, wherein said combining means comprises a WDM coupler.

54. The optical signal amplification apparatus according to claim 46, wherein said first beam wavelength λ_1 is about 1455nm.

55. The optical signal amplification apparatus according to claim 46, wherein said second beam wavelength λ_2 is about 1505nm.

56. A parallel optical amplification apparatus, said apparatus comprising:

a dividing means for dividing an optical signal having a wavelength between 1430nm and 1620nm at a predetermined wavelength λ_d into a first beam having a wavelength λ less than λ_d and a second beam having a wavelength greater than λ_d;

a broadband nonlinear polarization amplifier comprising

an input port for inputting said first beam;

a distributed gain medium for receiving said first beam and amplifying and spectrally broadening said first beam therein through nonlinear polarization, said distributed gain medium having zero-dispersion at wavelength λ_0;

a pumping means operated at wavelength λ_p for generating a pumping light to pump said distributed gain medium; and

an output port for outputting said amplified and spectrally broadened first beam,

wherein $\lambda \geq \lambda_0 \geq \lambda_p$, and

said pumping light cascades through said distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$);

an erbium-doped fiber amplifier for receiving said second beam and producing an amplified broadband second beam; and

means for combining said amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal.

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57. The optical signal amplifying apparatus according to claim 56, wherein said predetermined wavelength λ_d is about 1525nm.

58. The optical signal amplifying apparatus according to claim 56, wherein said dividing means comprises a WDM coupler.

59. The optical signal amplifying apparatus according to claim 56, wherein said combining means comprises a WDM coupler.

60. A method of producing an amplified broadband optical signal, said method comprising:

inputting an optical signal having a wavelength λ to a distributed gain medium having a zero-dispersion wavelength λ_0;

generating a pumping light from a pumping means operated at a wavelength λ_p;

pumping said distributed gain medium with said pumping light to amplify said optical signal;

cascading said pumping light through said distributed gain medium a plurality of Raman orders, the wavelength λ_p being such that an intermediate Raman order has a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0;

phase matching said intermediate Raman order with four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$) for spectral broadening; and

outputting said amplified and spectrally broadened optical signal, wherein $\lambda \geq \lambda_0 \geq \lambda_p$.

61. The method of producing an amplified broadband optical signal according to claim 60, wherein said wavelengths λ_r and λ_0 satisfy the following relationship:

$$|\lambda_r - \lambda_0| \leq 5\text{nm}.$$

62. The method of producing an amplified broadband optical signal according to claim 60, wherein said distributed gain medium is an optical fiber.

63. The method of producing an amplified broadband optical signal according to claim 60, wherein said distributed gain medium is a standard dispersion fiber having a zero-dispersion wavelength λ_0 of about 1310nm.

64. The method of producing an amplified broadband optical signal according to claim 60, wherein said distributed gain medium comprises first and second optical

fibers spliced together, and said optical fibers are used for two different cascad d Raman orders and have a zero-dispersion wavelength λ_0 at about 1310nm and 1390nm respectively.

65. The method of producing an amplified broadband optical signal according to claim 60, wherein said distributed gain medium is a dispersion-flattened fiber with low dispersion at least between about 1310nm and 1390nm.

66. A method of producing an amplified broadband optical signal, said method comprising:

inputting an optical signal having a wavelength λ between about 1430nm and 1530nm to an optical fiber having zero-dispersion at wavelength λ_0 and a cut-off wavelength less than 1240nm;

generating a pumping light from a pumping means operated at a wavelength of 1240nm;

pumping said optical fiber with said pumping light for amplifying said optical signal;

cascading said pumping light through said distributed gain medium a plurality of Raman orders, an intermediate Raman order having a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0;

phase matching said intermediate Raman order with four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$) for spectral broadening; and

outputting said amplified and spectrally broadened optical signal, wherein $\lambda \geq \lambda_0 \geq 1240$nm.

67. The method of producing an amplified broadband optical signal according to claim 66, further comprising a step of increasing pumping conversion efficiency by retroreflecting a beam from the optical fiber.

68. The method of producing an amplified broadband optical signal according to claim 66, further comprising a

step of using an isolator to prevent lasing from spurious feedback.

69. A method of producing an amplified broadband optical signal, said method comprising:

providing a Sagnac Raman cavity comprising a broadband mirror, and a loop mirror comprising of a Raman gain fiber and an optical coupler connected thereto, said fiber having a zero-dispersion wavelength λ_0 and a cut-off wavelength λ_{co};

inputting an optical signal having a wavelength λ between about 1430nm and 1530nm to said gain fiber;

generating a pumping light from a pumping means operated at a wavelength λ_p;

pumping said gain fiber with said pumping light for amplifying said optical signal;

cascading said pumping light through said gain fiber a plurality of Raman orders, the wavelength λ_p being such that an intermediate Raman order has a wavelength λ_r at a close proximity to said zero-dispersion wavelength λ_0;

phase matching said intermediate Raman order with four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$) for spectral broadening; and

outputting said amplified and spectrally broadened optical signal, wherein $\lambda \geq \lambda_0 \geq \lambda_p$.

70. The method of producing an amplified broadband optical signal according to claim 69, said method further comprising a step of controlling the polarization state in said Sagnac Raman cavity.

71. A method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1530nm, said method comprising:

dividing an optical signal at a predetermined wavelength into a first beam having a wavelength less than

said predetermined wavelength and a second beam having a wavelength greater than said predetermined wavelength;

directing said first beam to a first broadband nonlinear polarization amplifier according to claim 1 for amplifying and spectrally broadening said first beam;

directing said second beam to a second broadband nonlinear polarization amplifier according to claim 1 for amplifying and spectrally broadening said second beam; and

combining said amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal.

72. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1530nm according to claim 71, wherein said predetermined wavelength is about 1480nm, the zero-dispersion wavelength of said first amplifier is about 1365nm, and the zero-dispersion wavelength of said second amplifier is about 1328nm.

73. A method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm, said method comprising:

dividing an optical signal at a predetermined wavelength into a first beam having a wavelength less than said predetermined wavelength and a second beam having a wavelength greater than said predetermined wavelength;

directing said first beam to a Raman amplifier for amplifying and spectrally broadening said first beam;

directing said second beam to a rare earth doped amplifier for amplifying and spectrally broadening said second beam; and

combining said amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal.

74. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm

according to claim 73, wherein said Raman amplifier is a broadband nonlinear polarization amplifier according to claim 1.

75. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm according to claim 73, wherein said rare earth doped amplifier is an erbium-doped fiber amplifier.

76. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm according to claim 73, wherein said predetermined wavelength is about 1525nm.

77. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm according to claim 76, wherein said Raman amplifier is a broadband nonlinear polarization amplifier according to claim 1.

78. The method of producing an amplified broadband optical signal having a wavelength between 1430nm and 1620nm according to claim 76, wherein said rare earth doped amplifier is an erbium-doped fiber amplifier.

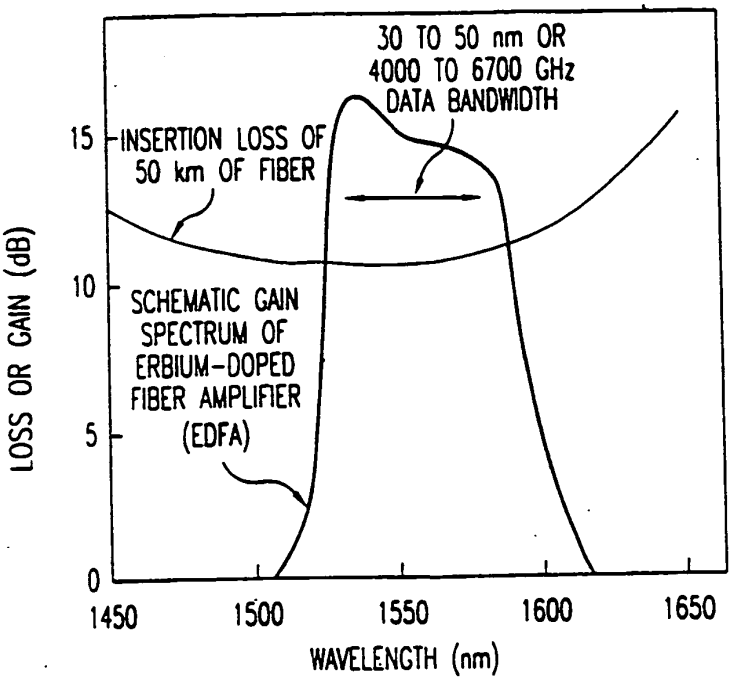

FIG.1
PRIOR ART

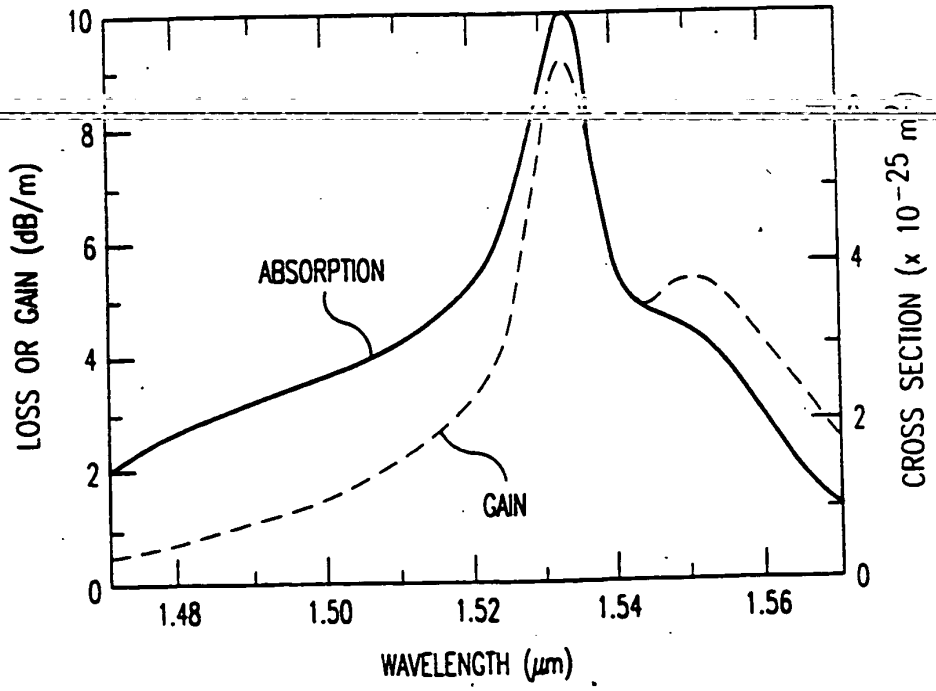

FIG.2
PRIOR ART

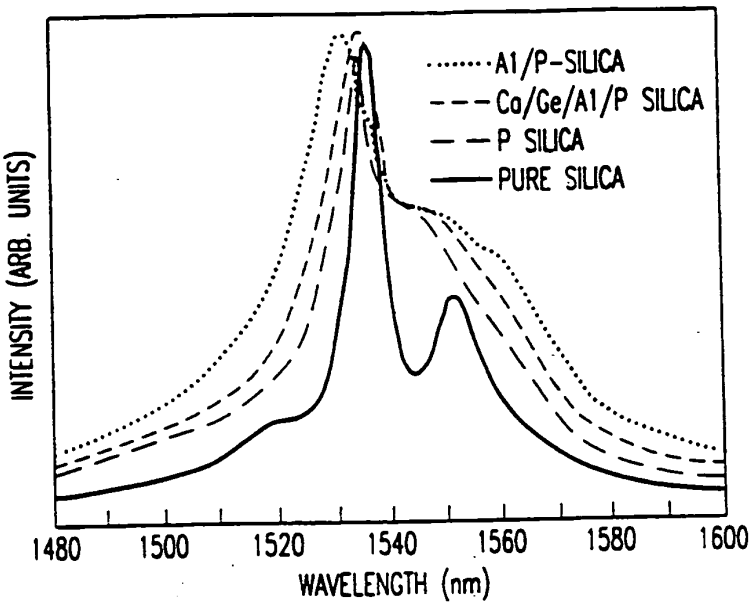

FIG.3a
PRIOR ART

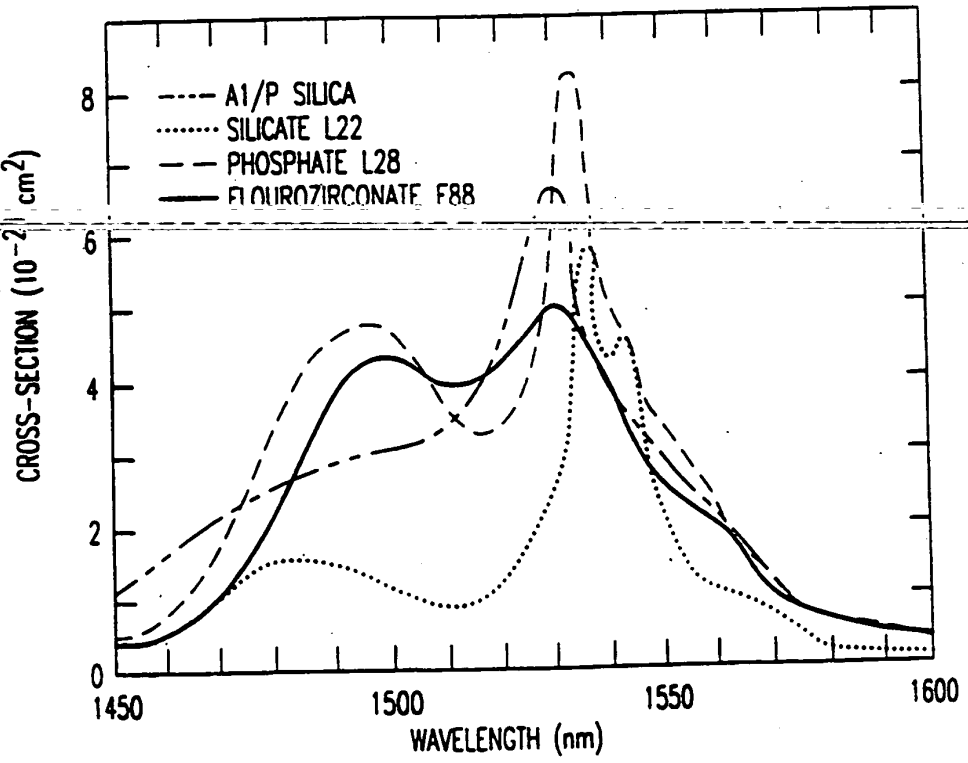

FIG.3b
PRIOR ART

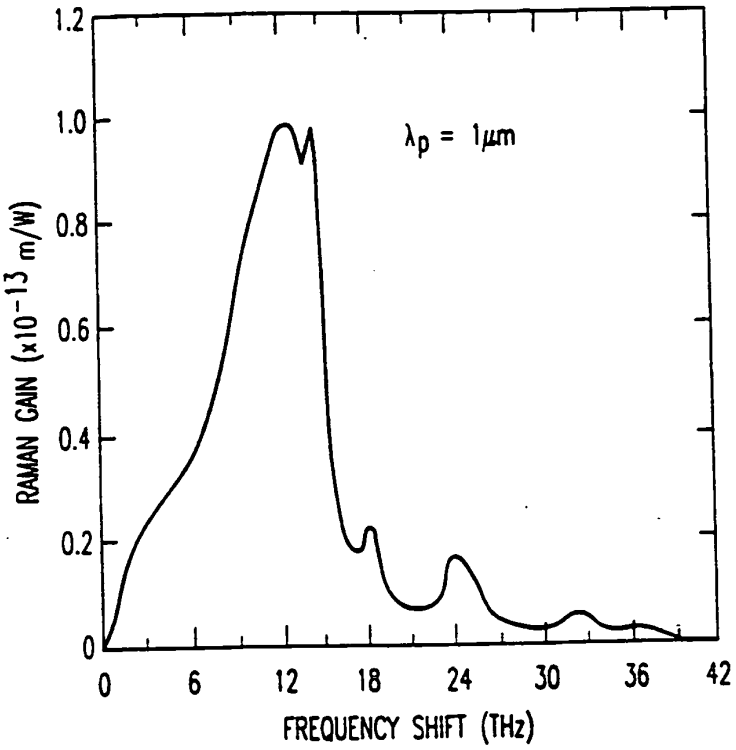

FIG.4
PRIOR ART

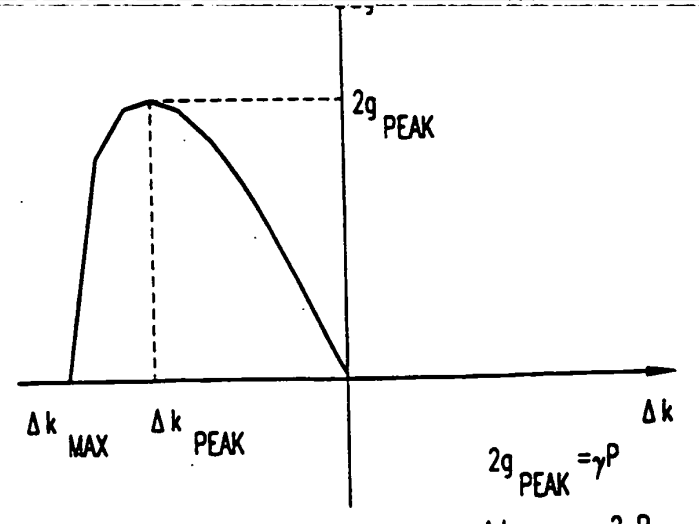

FIG.5

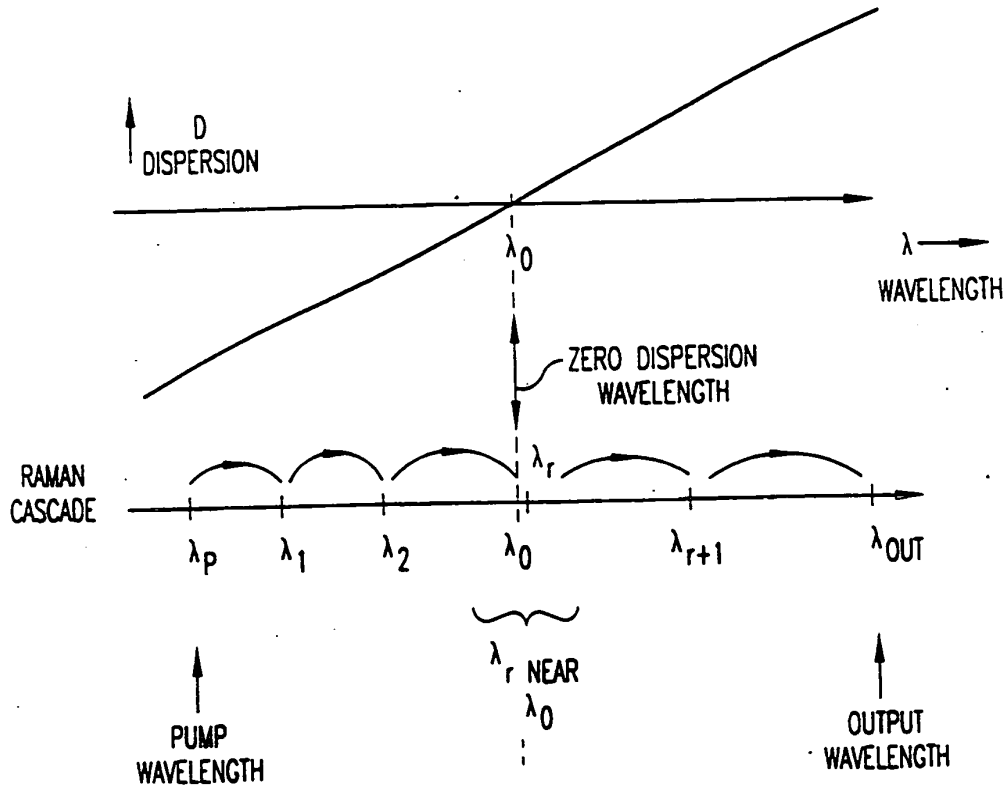
D
DISPERSION
λ0
λ
WAVELENGTH
ZERO DISPERSION
WAVELENGTH
λr
RAMAN
CASCADE
λP
λ1
λ2
λ0
λr+1
λOUT
λr NEAR
λ0
PUMP
WAVELENGTH
OUTPUT
WAVELENGTH

FIG.6

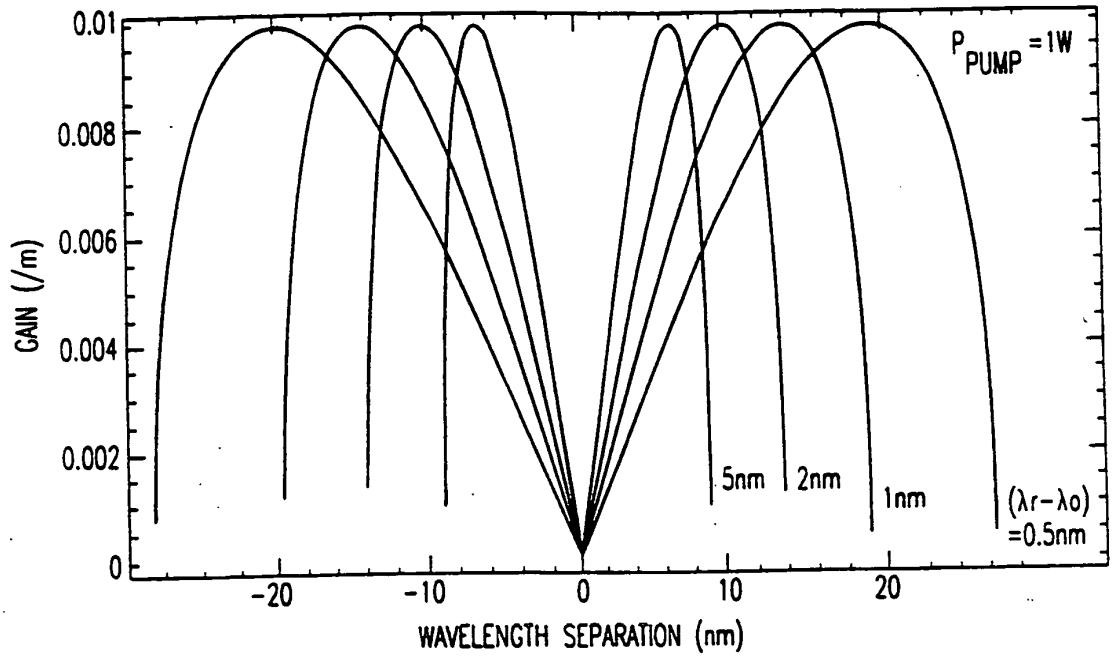
0.01
0.008
0.006
0.004
0.002
0
GAIN (/m)
-20
-10
0
10
20
WAVELENGTH SEPARATION (nm)
P_{PUMP} =1W
5nm
2nm
1nm
(λr-λo)
=0.5nm

FIG.7

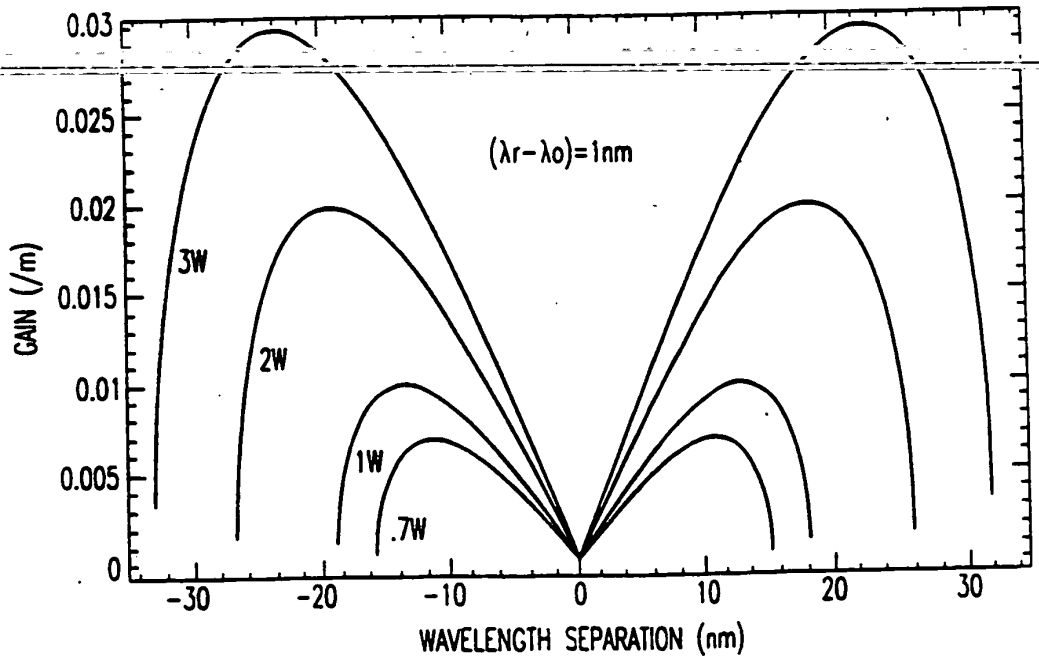
0.03
0.025
0.02
0.015
0.01
0.005
0
GAIN (/m)
-30
-20
-10
0
10
20
30
WAVELENGTH SEPARATION (nm)
(λr-λo)=1nm
3W
2W
1W
.7W

FIG.8

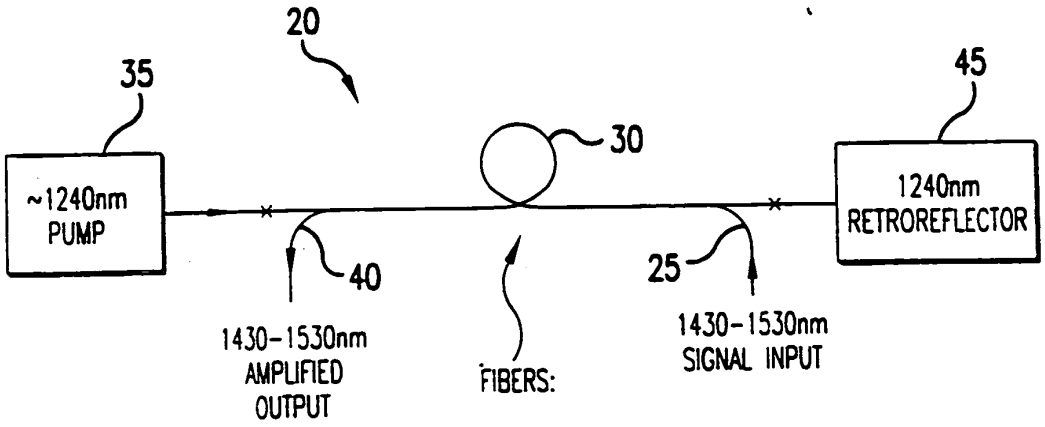

FIG.9

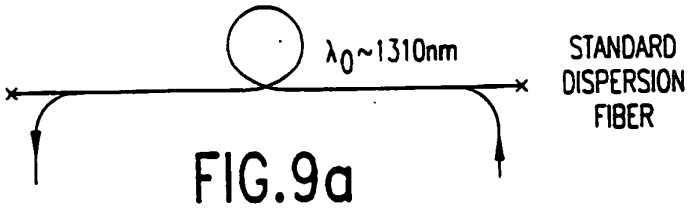

FIG.9a

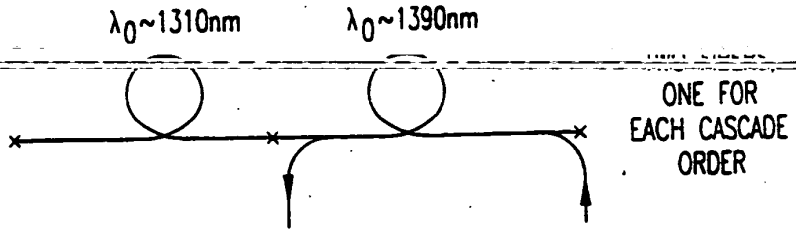

FIG.9b

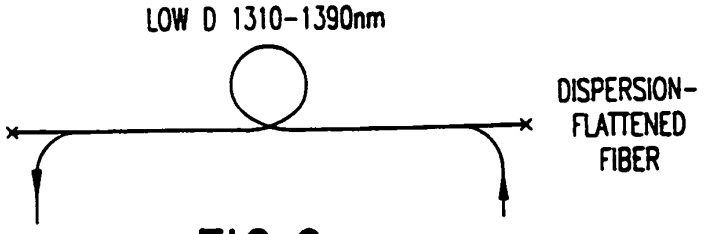

FIG.9c

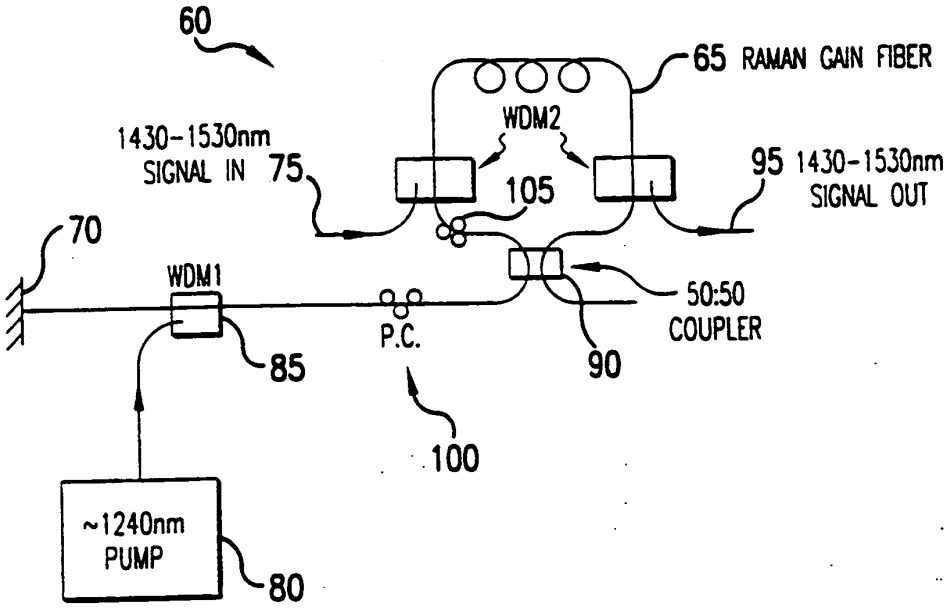
60
65 RAMAN GAIN FIBER
WDM2
1430-1530nm
SIGNAL IN 75
105
95 1430-1530nm
SIGNAL OUT
70
WDM1
50:50
COUPLER
P.C.
85
90
100
~1240nm
PUMP
80

FIG.10

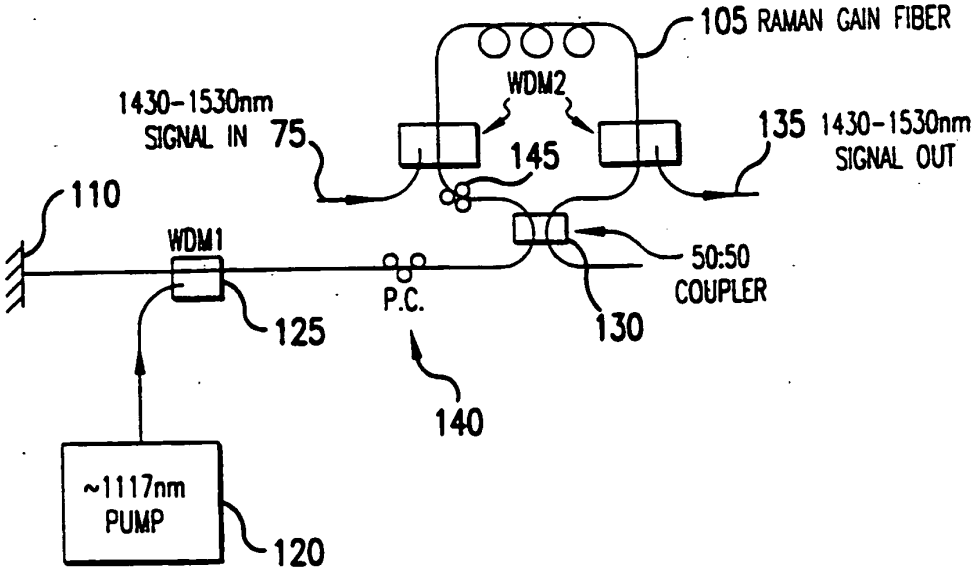
105 RAMAN GAIN FIBER
WDM2
1430-1530nm
SIGNAL IN 75
145
135 1430-1530nm
SIGNAL OUT
110
WDM1
50:50
COUPLER
P.C.
125
130
140
~1117nm
PUMP
120

FIG.11

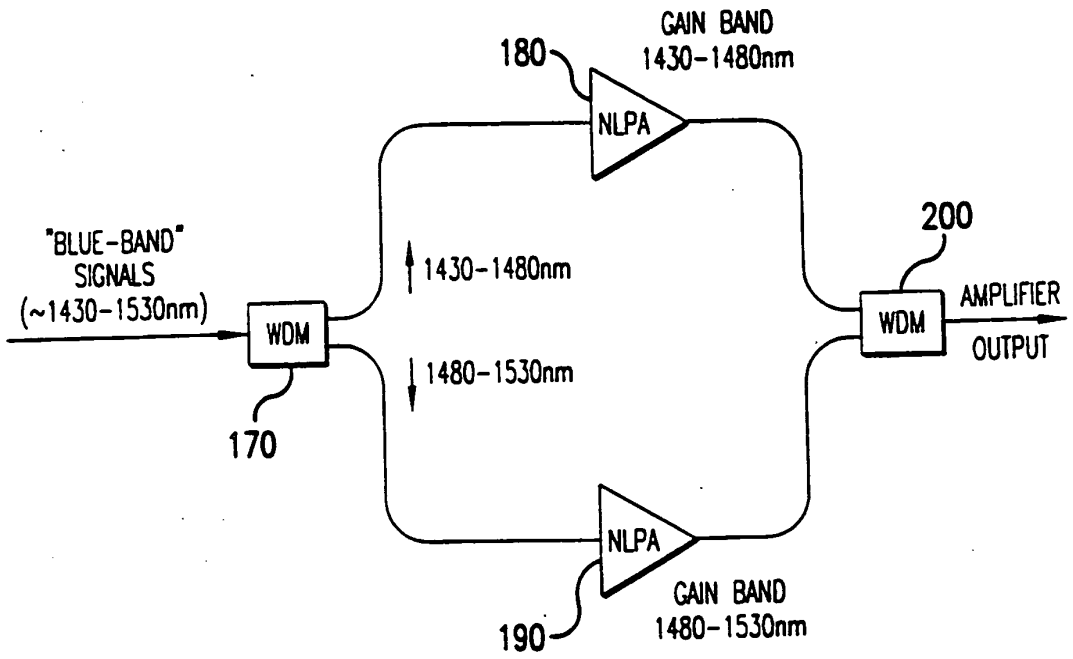
GAIN BAND
1430-1480nm
180
NLPA
200
"BLUE-BAND"
SIGNALS
(~1430-1530nm)
1430-1480nm
WDM
WDM
AMPLIFIER
OUTPUT
1480-1530nm
170
NLPA
GAIN BAND
1480-1530nm
190

FIG.12

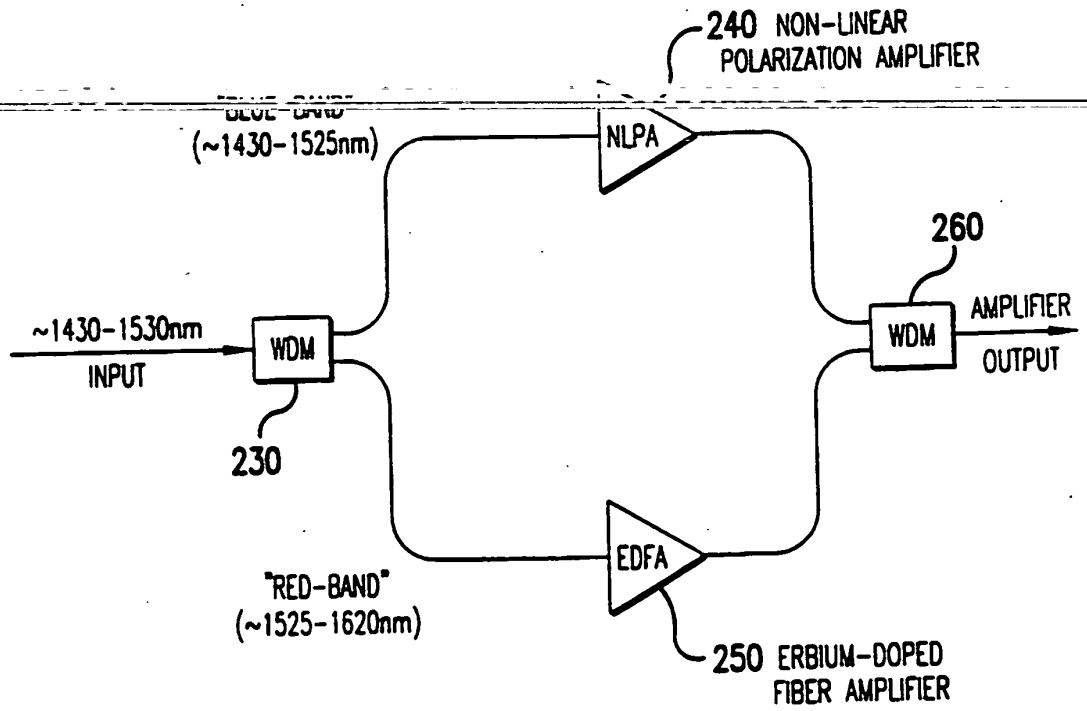
240 NON-LINEAR
POLARIZATION AMPLIFIER
(~1430-1525nm)
NLPA
260
~1430-1530nm
INPUT
WDM
WDM
AMPLIFIER
OUTPUT
230
EDFA
"RED-BAND"
(~1525-1620nm)
250 ERBIUM-DOPED
FIBER AMPLIFIER

FIG.13

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